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14. ABSTRACT

The Committee was charged with assessing our state of knowledge of underwater noise and recommending research areas to assist in determining whether noise in the ocean adversely affects marine mammals. The committee was selected to represent a diverse range of expertise, including acousticians and marine biologists, as well as an expert in geophysical exploration. The committee convened four times, including three open public sessions. A wide variety of experts in the field of marine mammals and noise addressed the committee and submitted materials for review.

One of the challenges in preparing the report was to standardize the units of measure. Another was to clarify commonly used terms in underwater acoustics, seismic exploration, and marine mammology. Remarkably few details are known about the characteristics of ocean noise, whether it be of human or natural origin, and much less is understood of the impact of noise on the short- and long-term well-being of marine mammals and the ecosytems on which they depend.

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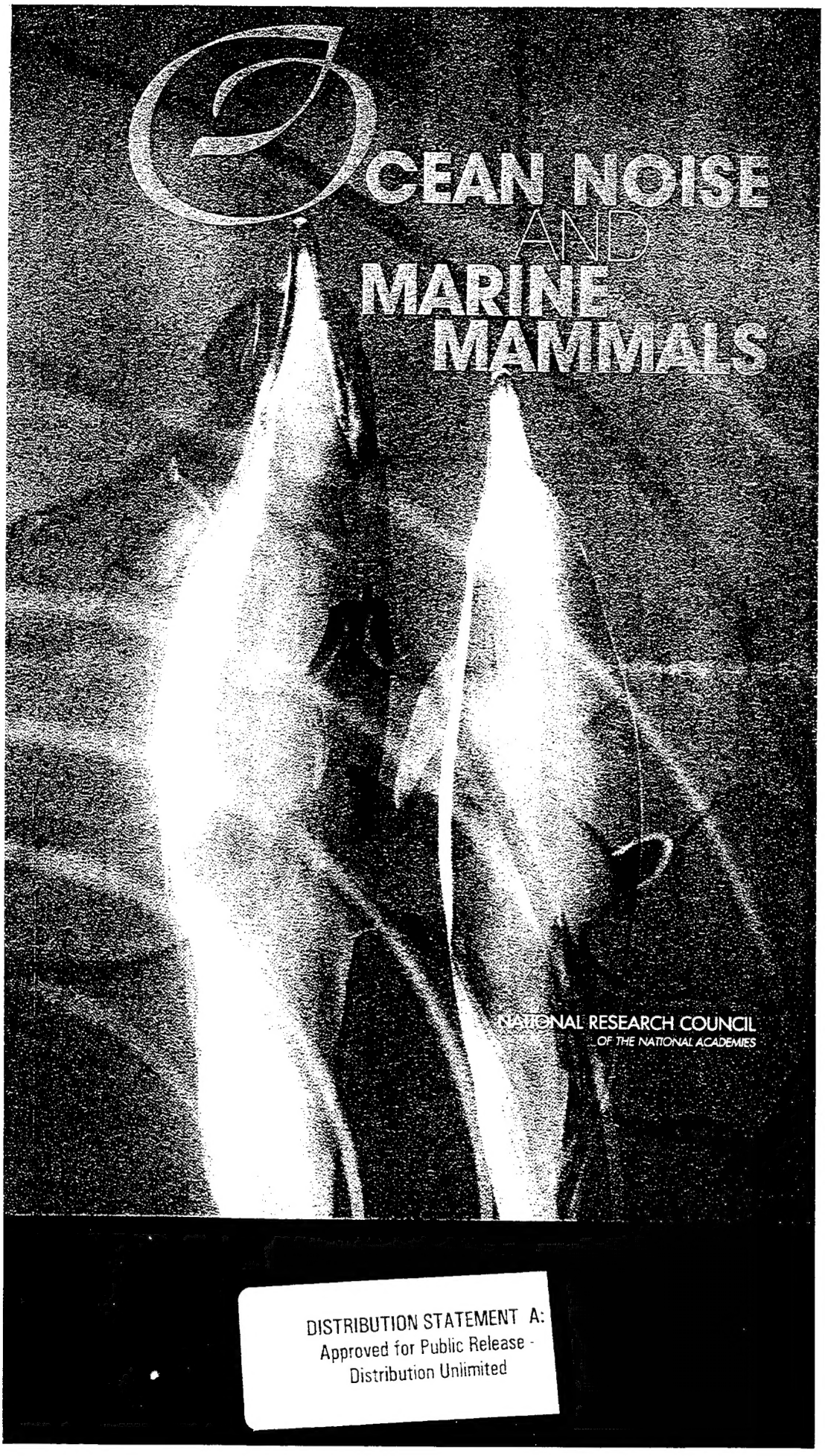

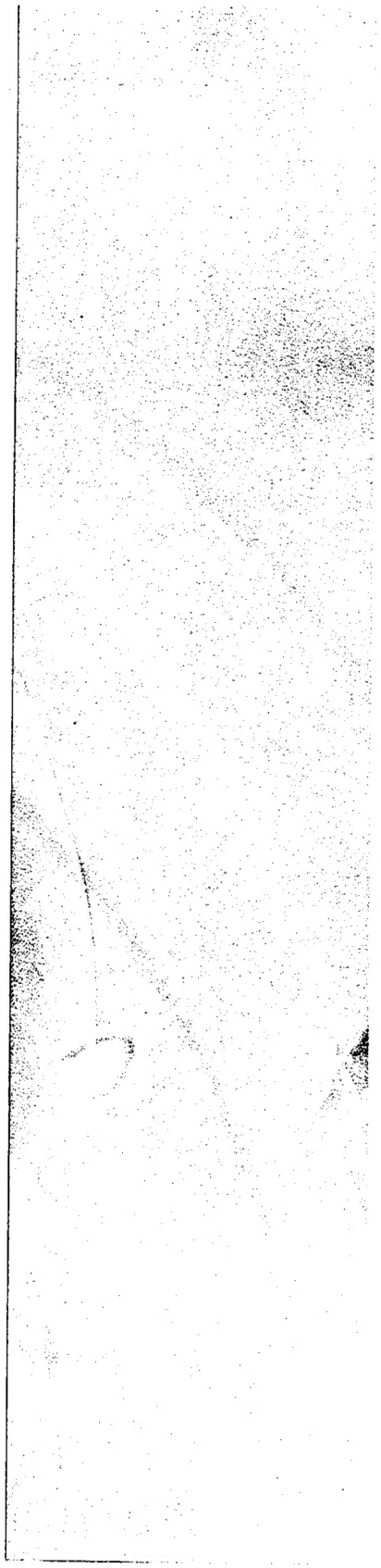

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

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COMMITTEE ON POTENTIAL IMPACTS OF AMBIENT NOISE IN THE OCEAN ON MARINE MAMMALS

GEORGE FRISK, *Chair*, Woods Hole Oceanographic Institution, Massachusetts
DAVID BRADLEY, Pennsylvania State University, State College
JACK CALDWELL, WesternGeco, Houston, Texas
GERALD D'SPAIN, Scripps Institution of Oceanography, San Diego, California
JONATHAN GORDON, Gatty Marine Laboratory, St. Andrews, Scotland
MARDI HASTINGS, Ohio State University, Columbus (resigned 2002)
DARLENE KETTEN, Woods Hole Oceanographic Institution, Massachusetts
JAMES MILLER, University of Rhode Island, Narragansett
DANIEL L. NELSON, BBN Technologies, Cambridge, Massachusetts
ARTHUR N. POPPER, University of Maryland, College Park
DOUGLAS WARTZOK, Florida International University, Miami

Staff

MORGAN GOPNIK, Board Director
JENNIFER MERRILL, Study Director
ROBIN MORRIS, Financial Officer
JULIE PULLEY, Project Assistant

The work of this committee was overseen by the Ocean Studies Board of the National Research Council.

Executive Summary

In recent years, both the scientific community and the general public have become increasingly aware of—and concerned about—conserving the earth's marine resources. Heightened concerns are evident from the increase of scientific and popular articles devoted to such topics as beach closures, harmful algal blooms, and marine mammal strandings. Among the most sensitive and controversial yet least understood subjects is the effect of human-generated noise on marine mammals. Scientists and laypersons alike are well aware that human-generated sound in the sea comes from a variety of sources, including commercial ship traffic, oil exploration and production, construction, acoustic research, and sonar use. Underwater sounds are also generated by natural occurrences such as wind-generated waves, earthquakes, rainfall, and marine animals. It is well known that noise levels in the sea began to increase steadily with the onset of industrialization in the mid-nineteenth century. The conventional assumption is that this trend has continued in recent times as well, but there is only limited scientific evidence to support this hypothesis. Many factors have combined to escalate the awareness of and concern for noise impacts on marine mammals and on their habitat, supporting communication systems, and behavior. However, remarkably few details are known about the characteristics of ocean noise, whether it be of human or natural origin, and much less is understood of the impact of noise on the short- and long-term well-being of marine mammals and the ecosystems on which they depend.

It was in this context of these uncertainties that the current committee effort began. At the request of the federal interagency National Ocean Partnership Program, with sponsorship from the Office of Naval Research,

the National Oceanic and Atmospheric Administration, the National Science Foundation, and the U.S. Geological Survey, the National Research Council (NRC) of the National Academies undertook a study to examine the current state of knowledge on ocean noise and its effects on marine mammals. The NRC was asked to

- evaluate the human and natural contributions to marine ambient noise and describe the long-term trends in ambient noise levels, especially from human activities;
- outline the research needed to evaluate the impacts of ambient noise from various sources (natural, commercial, naval, and acoustic-based ocean research) on marine mammal species, especially in biologically sensitive areas;
- review and identify gaps in existing marine noise databases; and
- recommend research needed to develop a model of ocean noise that incorporates temporal, spatial, and frequency-dependent variables (Box 1).

The committee held three public meetings and received input from underwater acousticians, marine mammalogists, auditory physiologists, and naval oceanographers. The committee reviewed previous NRC reports (NRC, 1994, 2000), current scientific articles, symposium reports, models, and data compiled by the Naval Oceanographic Office.

This report is the third in a series by the NRC examining the potential effects of ocean noise on marine mammals. Although the three reports evolved from very different charges and were generated by separate committees, many similar research needs became evident during each study. The recommendations presented in this report build on, but do not replace, those presented in the earlier efforts (NRC, 1994, 2000). This committee recommends that all three reports be examined in order to better understand the research needs required to mitigate the effects of human-generated ocean noise on the marine ecosystem.

FINDINGS

For the purposes of evaluating the potential effects of underwater sound on the marine environment, both ambient noise and noise from identifiable sources must be considered. The term "ambient noise" is used by the underwater acoustics community to refer to the background din emanating from a myriad of unidentified sources. Although the type of noise source may be known, the specific sources are not identified. When examining the possible effects of ocean noise on marine mammals noise from specific sources is also important; therefore, the term "ocean noise" will be used in this report to refer to all types of noise sources.

Sound in the ocean is generated by a broad range of sources, both natural and human (anthropogenic), for intentional use or as the unintended consequence of activity in the ocean. Natural geophysical sources include wind-generated waves, earthquakes, precipitation, and cracking ice. Natural biological sounds include whale songs, dolphin clicks, and fish vocalizations. Anthropogenic sounds are generated by a variety of activities, including commercial shipping, geophysical surveys, oil drilling and production, dredging and construction, sonar systems, and oceanographic research. Intentional sounds are produced for an explicit purpose, such as seismic surveying to find new fossil fuel reservoirs. Unintentional sounds are generated as a byproduct of some other activity, such as noise radiated by a ship's machinery as it crosses the ocean.

A proper accounting of the global ocean noise budget must include both the background ambient component and the contributions from identifiable sources. An overall global noise budget typically is derived by averaging the received noise spectrum over space and time. Contributions from transient-in-time and localized-in-space components are lost in this averaging process. This conventional accounting technique suggests that the two largest contributors to the overall (space- and time-averaged) deep-ocean noise budget are wind-generated ocean waves over the frequency band from 1 Hz to at least 100 kHz and commercial shipping at low frequencies (from 5 Hz to a few hundred Hz). However, it is clear also that this method is only one approach to computing the noise budget and is not necessarily the most appropriate one for assessing the impact of sound on marine mammals.

There are very limited data to determine long-term trends in ocean noise levels. While noise levels in the ocean began to increase with the onset of the Industrial Revolution (ca. 1850), it is much less clear that this trend is continuing in the twenty-first century. Commercial shipping noise is actually the only area for which educated speculation on long-term trends is possible. On one hand, the substantial increase in the number of commercial vessels during the past 50 years, supplemented by limited noise observations, implies there has been a gradual increase in noise levels from ship traffic on the order of 15 dB. On the other hand, newer ships may be quieter, and the relationship between ship-radiated noise and ship parameters (e.g., gross tonnage, length, and speed) is not sufficiently understood to develop a reliable predictive capability. Although evidence on long-term trends in ocean noise characteristics is very limited and there is even less evidence on the effects of ocean noise on marine life, present data are sufficient to warrant increased research and attention to trends in ocean noise.

There are very limited observations concerning the effects of ocean noise on marine mammals. Short- and long-term effects on marine mammals of ambient and identifiable components of ocean noise are poorly

Box 1
Overview of the Committee's Research Recommendations

To Evaluate Human and Natural Contributions to Ocean Noise

- Gather together in one location existing data on man-made sources and noise;
- Measure alternative properties of man-made sources in addition to average acoustic pressure spectral level;
- Establish a long-term ocean noise monitoring program covering the frequency band from 1 to 200,000 Hz;
- Monitor ocean noise in geographically diverse areas with emphasis on marine mammal habitats;
- Develop quantitative relationships between man-made noise and levels of human activity;
- Conduct research on the distribution and characteristics of marine mammal sounds;
- Develop a global ocean noise budget that includes both ambient and transient events and uses "currencies" different from average pressure spectral levels to make the budget more relevant to marine mammals.

To Describe Long-Term Trends in Ocean Noise Levels, Especially from Human Activities

- Establish a long-term ocean noise monitoring program covering the frequency band from 1 to 200,000 Hz;
- Develop quantitative relationships between man-made noise and levels of human activity.

Research Needed to Evaluate the Impacts of Ocean Noise from Various Sources on Marine Mammal Species

- Measure effects of alternative properties of man-made sources in addition to average acoustic pressure spectral level on marine mammals;
- Establish a long-term ocean noise monitoring program covering the frequency band from 1 to 200,000 Hz;
- Monitor ocean noise in geographically diverse areas with emphasis on marine mammal habitats;
- Try to structure all research on marine mammals to allow predictions of population-level consequences;
- Identify marine mammal distributions globally;
- Conduct research on the distribution and characteristics of marine mammal sounds;
- Develop short-term, high-resolution, and long-term tracking tagging technologies;

- Search for subtle changes in behavior resulting from masking;
- Search for noise-induced stress indicators;
- Examine the impact of ocean noise on nonmammalian species in the marine ecosystem;
- Continue integrated modeling efforts of noise effects on hearing and behavior;
- Develop a marine-mammal-relevant global ocean noise budget;
- Investigate the causal mechanisms for mass strandings and observed traumas of beaked whales.

Current Gaps in Existing Ocean Noise Databases

- Gather together in one location existing data on man-made sources and noise;
- Measure alternative properties of man-made sources in addition to average acoustic pressure spectral level;
- Establish a long-term ocean noise monitoring program covering the frequency band from 1 to 200,000 Hz and which includes transients;
- Monitor ocean noise in geographically diverse areas with emphasis on marine mammal habitats;
- Conduct research on the distribution and characteristics of marine mammal sounds.

To Develop a Model of Ocean Noise that Incorporates Temporal, Spatial, and Frequency-Dependent Variables

- Gather together in one location existing data on man-made sources and noise;
- Measure alternative properties of man-made sources in addition to average acoustic pressure spectral level;
- Establish a long-term ocean noise monitoring program covering the frequency band from 1 to 200,000 Hz (data are critical for model validation);
- Monitor ocean noise in geographically diverse areas with emphasis on marine mammal habitats;
- Develop quantitative relationships between man-made noise and levels of human activity;
- Conduct research on the distribution and characteristics of marine mammal sounds;
- Incorporate distributed sources into noise effects models;
- Develop a marine-mammal-relevant global ocean noise budget.

Administrative Recommendations

- Provide a mandate to a single federal agency to coordinate ocean noise monitoring and research, and research on effects of noise on the marine ecosystem;
- Educate the public.

understood. There is no documented evidence of ocean noise being the direct physiological agent of marine mammal death under any circumstances. On the other hand, marine mammals have been shown to change their vocalization patterns in the presence of background and anthropogenic noise. Furthermore, the long-term effects of ambient noise on marine organisms are even less well understood. Potential effects include changes in hearing sensitivity and behavioral patterns, as well as acoustically induced stress and impacts on the marine ecosystem.

Models describing ocean noise are better developed than models describing marine mammal distribution, hearing, and behavior. The biggest challenge lies in integrating the two types of models. A wide variety of ambient noise models and databases have been developed by the U.S. Navy as part of its antisubmarine warfare effort. However, the focus on naval scenarios means that they are not ideally suited for marine mammal applications. Models of marine mammal habitats and distribution patterns, as well as effects models linking dosage and response, are severely limited by a paucity of data. To provide a product that is useful for understanding and managing interactions between marine mammals and noise, existing databases must be expanded, updated, and coordinated to allow the integration of both marine mammal and ocean noise models. Well-documented databases also are essential for performing the critical step of model validation.

Recent reports both in the press and from federal and scientific sources indicate that there is an association between the use of high-energy mid-range sonars and some mass strandings of beaked whales. Recent mass strandings of beaked whales have occurred in close association, both in terms of timing and location, with military exercises employing multiple high-energy, mid-frequency (1-10 kHz) sonars. In addition, a review of earlier beaked whale strandings further reinforces the expectation that there is at least an indirect relationship between the strandings and the use of multiple mid-range sonars in military exercises in some nearshore beaked whale habitats. Several press reports about the recent incidents appeared while this report was in preparation and attributed the strandings to "acoustic trauma." Acoustic trauma is a very explicit form of injury. In the beaked whale cases to date, the traumas that were observed can result from many causes, both directly and indirectly associated with sound, but similar traumas have been observed in terrestrial mammals under circumstances having no relation to sound exposure. Careful sampling and analysis of whole animals have rarely been possible in the beaked whale cases so far, which has made definitive diagnoses problematic. As of this writing, eight specimens in relatively fresh condition have been rigorously analyzed. Because of the repeated associations in time and location of the strandings and sonar in military exercises, the correlation between sonars and the strandings is compelling, but that association is not synonymous with a causal mechanism for the deaths of the stranded animals. The cause of

death in all cases was attributed to hyperthermia, but a precise cause for the unusual traumas that were also seen in the cases examined has not yet been determined. The NATO/SACLANT Undersea Research Center report (D'Amico and Verboom, 1998) and the joint NOAA-Navy interim report (Evans and England, 2001) have not been discussed in detail in this document because of the preliminary nature of the findings. However, this is clearly a subject needing much additional research. The research program outlined in Evans and England is a good start.

RECOMMENDATIONS

A federal agency should be mandated to investigate and monitor marine noise and the possible long-term effects on marine life by serving as a sponsor for research on ocean noise, the effects of noise on marine mammals, and long-term trends in ocean noise. Federal leadership is needed to (1) monitor ocean noise, especially in areas with resident marine mammal populations; (2) collect and analyze existing databases of marine activity; and (3) coordinate research efforts to determine long-term trends in marine noise and the possible consequences for marine life.

Existing data on marine noise from anthropogenic sources should be collected, centralized, organized, and analyzed to provide a reference database, to establish the limitations of research to date, and to better understand noise in the ocean. Currently, data regarding noise produced by shipping, seismic surveying, oil and gas production, marine and coastal construction, and other marine activities are either not known or are difficult to analyze because they are maintained by separate organizations such as industry database companies, shipping industry groups, and military organizations. It would be advantageous to have all data in a single database in order to improve the ability of interested parties to access the data sets and use them in research, for scientific publications, in education, and for management and regulatory purposes. This database could be a distributed network of linked databases, using a standardized series of units of measure. International cooperation in this database development effort as well as international access to the information should be encouraged, since the marine mammal and ocean noise issue is global.

Acoustic signal characteristics of anthropogenic sources (such as frequency content, rise time, pressure and particle velocity time series, zero-to-peak and peak-to-peak amplitude, mean squared amplitude, duration, integral of mean squared amplitude over duration, repetition rate) should be fully reported. Each characteristic of noise from anthropogenic sources may differentially impact each species of marine mammals. The complex interactions of sound with marine life are not sufficiently understood to specify which features of the acoustic signal are important for specific impacts. Therefore as many characteristics as possible should be measured

and reported. For transients, publication of actual acoustic pressure time series would be useful. Experiments that expose marine mammals to variations in these characteristics should be conducted in order to determine the physiological and behavioral responses to different characteristics. Particular attention should be paid to the sources that are likely to be the large contributors to ocean noise in especially significant geographical areas and to sources suspected of having significant impacts on marine life.

A long-term ocean noise monitoring program over a broad frequency range (1 Hz to 200 kHz) should be initiated. Monitoring and data analysis should include average or steady-state ambient noise as well as identifiable sounds such as seismic surveying sources, sonars, and explosive noises that are not identified in classical ambient noise data sets. Acoustic data collection should be incorporated into global ocean observing systems initiated and under discussion in the United States and elsewhere. A research program that develops a predictive model of long-term noise trends should be initiated. Data from monitoring systems should be available in a timely manner to facilitate informed decision making by interested industry, military, and marine researchers, operators, and regulatory agencies.

Efforts to measure ocean noise should be targeted toward important marine mammal habitats. Until these habitats are fully described, it is reasonable to begin a long-term monitoring program in coastal areas, locations close to known marine mammal migration paths, foraging areas, and breeding grounds. As new marine mammal habitats are identified, these should be added to the acoustic surveys in order to provide a complete picture of the acoustic environment in important marine mammal ecosystems.

A research program should be instituted to investigate the possible causal relationships between the ambient and identifiable source components of ocean noise and their short- and long-term effects on marine organisms. Addressing this challenging and difficult problem will require a multidisciplinary effort between biologists and acousticians to establish a rigorous observational, theoretical, and modeling program. An initial significant focus of this work should be the examination of the possible relationship between the acoustics of identifiable high-energy, mid-frequency sonars, marine mammal trauma, and mass stranding events. In addition, a study of the potential influence of ambient noise on long-term animal behavior should be vigorously pursued.

Whenever possible, all research conducted on marine mammals should be structured to allow predictions of whether responses observed indicate population-level effects. Although it is difficult to obtain direct evidence of impacts of human activity on marine mammals, it is even more difficult to determine long-term impacts on individuals or impacts on populations. Although the few documented cases of direct impact on individuals have

raised awareness of potential population impacts, no measures exist of marine mammal population effects from ocean noise.

Research should be conducted beyond locales already known and studied to globally characterize marine mammal distributions and populations. Despite the large body of marine mammal research to date, including what was recommended in previous reports (e.g., NRC, 1994), there is a surprising lack of information regarding the global distribution of marine mammals. Migration routes, breeding grounds, and feeding areas are known for relatively few species. In order to predict the importance of noise effects on marine mammal behavior, the seasonal and geographic distribution of the mammals must be better known both through survey data and through the use of predictive oceanographic variables, such as topography, bottom type, and water column variables. This enormous task will require the development of new sampling and extrapolation techniques in order to be practically achievable.

Research to determine quantitative relationships between levels of anthropogenic activity and noise should be conducted. For example, if there is a robust relationship between vessel type and noise, vessel traffic data could be used to predict shipping noise. Identifying reliable indicators for anthropogenic sources will provide an additional modeling tool and predictive capability that will be particularly useful in areas where long-term monitoring may be difficult or impossible. Similar needs exist for every facet of human activity in the oceans.

Research should be undertaken to describe the distribution and characteristics of sounds generated by marine mammals and other marine organisms seasonally, geographically, and within behavioral contexts. While good progress has been made in describing marine mammal acoustic repertoires, much less is known about the details of natural patterns of sound production, including the means of production and context in which different vocalizations are produced, as well as how they vary diurnally, seasonally, and geographically. Marine mammals themselves may be significant sources of ocean noise, although possibly in localized areas over limited time periods. These studies will also shed light on the contribution that marine organisms make to the global ocean noise budget.

Research should be conducted to determine subtle changes in marine mammal behavior, as well as failure to detect calls from other animals or echoes from their own echolocation, that might result from masking of biologically important acoustic information by anthropogenic sounds. Short-term responses of marine mammals to anthropogenic noise sources have been documented to a limited degree; however, long-term effects of marine noise on the behavior of marine mammals have received less attention. Impacts resulting from increases in background ambient noise have not been documented.

Marine mammal tagging studies should be continued to observe behavioral changes in response to acoustic cues and to provide important data for simulation models. Efforts to improve marine mammal tagging technology should continue to receive support. Two technological improvements of current tags are needed: (1) increase the duration of long-term data gathering tags from months to multiple years to observe annual behavior cycles and migration patterns, and (2) extend the duration of high-resolution tags from hours to days to gather more data on daily behavior and environmental cues. Current tagging technology allows individual marine mammals to be tracked up to months. Tags capable of higher-resolution data collection, including animal orientation, acceleration, and produced or received sounds, can generally collect data for less than one day. These data have proven very valuable in determining behavioral patterns in a variety of cetaceans and pinnipeds and correlating their behavior with environmental cues. The technology should continue to be developed to allow longer studies using both the high- and low-resolution tags.

Research efforts should seek to determine if reliable long-term stress indicators exist and if they can be used to differentiate between noise-induced stress and other sources of stress in representative marine mammal species. Stress indicators may be one useful marker for long-term effects of anthropogenic noise on marine mammals.

The impact of noise on nonmammalian organisms in the marine ecosystem should be examined. Fish use sound in many ways that are comparable to the ways marine mammals communicate and sense their environment. The effects of anthropogenic noise on fish and other nonmammalian species, including their eggs and larvae, are largely unknown. As cohabitants of the marine ecosystem and as members of the same food web, noise impacts on marine fish could, in turn, affect marine mammals.

Modeling efforts that integrate acoustic sources, propagation, and marine mammals should be continued and fully supported. Simulation models that predict the characteristics of the noise (frequency content, mean squared level, peak level, pressure time series, etc.) and their effects on marine mammals may assist in understanding and mitigating harmful effects of marine noise on mammals. At least one such effort is underway: the Effects of Sound on the Marine Environment model sponsored by the Office of Naval Research. Modeling some direct physiological effects on hearing (e.g., temporary or permanent threshold shift) is relatively straightforward, although limited by the small data sets available from a limited number of species. These integrative tools should be expanded to include the effects of sources of noise that may change their distribution over time such as shipping, wind-induced breaking waves, and distributed biological noise. More effort should be placed on modeling, both explicit marine species hearing models and behavioral effects models for all types of ocean noise.

A model of global ocean noise that properly reflects the impact of both ambient noise and noise from identified sources on marine mammals should

be developed and verified. The conventional approach that utilizes an average pressure spectrum budget is limited in its application to the marine mammal problem. A more comprehensive approach that encompasses contributions of both transient events and continuous sources to ocean noise should be pursued. Many of this committee's recommendations, particularly those concerning information on distribution and source signatures of man-made sources, must be addressed in order to have the capability to develop a marine-mammal-relevant global ocean noise model. In addition, since model validation is a critical part of the model development process, the committee's recommendations pertaining to the collection of high quality, well-documented ocean noise data sets must be pursued in tandem.

A program should be instituted to investigate carefully the causal mechanisms that may explain the traumas observed in beaked whales, whether this is a species-specific or broader issue, and how the acoustics of high-energy, mid-range sonars may directly or indirectly relate to mass stranding events. The research program outlined in Evans and England (2001) represents a good initial effort. The association of beaked whale mass strandings with high-energy, mid-range sonars has recently received much public attention, and the preliminary scientific findings of two such events have been released in agency reports but have not appeared in the peer-reviewed literature. Review of prior mass stranding reports for beaked whales further reinforces the probability of this relationship. In few cases have the beaked whale carcasses been in a condition to allow full, definitive forensic analyses. The complexity of obtaining appropriate samples from stranded beaked whales and the paucity of data to date, both from mass and nonmass strandings, prevent clearly determining the mechanisms and any causal relationship behind the traumas observed, the strandings per se, and sonar use.

The committee encourages the acoustical oceanography community, marine mammal biologists, marine bioacousticians, and other users of sound in the ocean, such as the military and oil industry, to make greater efforts to raise public awareness of fundamental acoustic concepts in marine biology and ocean science so that they are better able to understand the problems, the need for research, and the considerable potential for solving noise problems. The public, including environmental advocates, are very interested in anthropogenic noise in the ocean and its effect on marine animals. Recently there has been a communication gap between users of sound in the ocean, including scientists, and the public. Much of the gap in understanding between the ocean science community and the public arises from the public's lack of understanding of fundamental acoustic concepts and the scientific community's failure to communicate these concepts effectively. Source and received levels, propagation loss, air-water physical acoustic differences, and the term "decibel" are examples of concepts that have been misunderstood by the media, environmental organizations, and the general public.